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SUPPLEMENT 146

METHODS OF APPRAISING INTENSITY AND DESTRUCTIVENESS OF CEREAL RUSTS WITH PARTICULAR REFERENCE TO RUSSIAN WORK ON WHEAT LEAF RUST

April 1, 1944

F O R E W O R D

Dr. Chester's summary and discussion of methods of determining the intensity of and estimating losses from cereal rusts is an extremely useful contribution to the literature on survey procedures. Much of the material included is not readily available to American workers; particularly the important Russian work which as Dr. Chester shows, is so full of practicable suggestions.

This article sets a high standard and should prove a strong impetus toward achieving the "research level of plant disease surveying", one of Dr. Chester's own objectives.

The Reporter hopes the article may be of distinct service to all plant pathologists who are interested in the effects of the diseases that they study.

METHODS OF APPRAISING INTENSITY AND DESTRUCTIVENESS OF CEREAL RUSTS WITH PARTICULAR REFERENCE TO RUSSIAN WORK ON WHEAT LEAF RUST

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I. INTRODUCTION

The present intensification of plant disease survey activities, as pointed out at the meeting of the American Phytopathological Society in 1943, brings with it the need of improvements in the methodology of plant disease surveying. During the past quarter-century a number of Russian phytopathologists have given particular attention to means for improving the accuracy of estimating the intensity and destructiveness of plant diseases. The contributions of the Russian workers include a number of original procedures which well merit the study of American phytopathologists, but which as yet do not appear to be generally recognized. This may be largely due to the fact that the Russian work, almost without exception, has appeared in Russian journals, some of them of small circulation and little known, and without summaries in the other languages of science that are more familiar to American workers; a number of these papers have escaped the abstracting journals, and where English or German abstracts have been published, these usually have devoted themselves principally to experimental results, and have been given very inadequate information on the methodological details.

This digest of Russian contributions on survey methods has been prepared in the belief that some of them may find application under American conditions. It is limited to an analysis of techniques used in appraising the cereal rusts, a field in which Russian workers have been notably active, and refers in particular to wheat leaf rust (*Puccinia triticina* Erikss.), which, as it is the most destructive of the cereal rusts in Russia (19), has received special attention at the hands of pathologists in that country. Contributions from workers in other countries are mentioned only to the extent that they provide necessary background for an understanding of the Russian work.

II. METHODS FOR DETERMINING INTENSITY OF RUSTS

1. Standards of measurement. In 1892, Cobb (5) in Australia published what appears to be the first diagrammatic scale for estimating the intensity of cereal rusts. This scale is essentially the same as that in general use for cereal rust estimation in the United States, and is known variously in the literature as the "American scale", the "U. S. Department of Agriculture scale", and the "scale of Melchers and Parker." It was adopted shortly before 1917 and appears to have been first published by Melchers and Parker in 1922 (20). The U.S.D.A. scale is a duplicate of the Cobb

scale with the addition of one grade of rustiness (that indicated as "65%" on the U.S.D.A. scale). The 5 grades on the Cobb scale were designated 1, 5, 10, 20, and 50% and those on the American scale 5, 10, 25, 40, 65, and 100% respectively, the greatest rust intensity in each case being represented by an actual coverage of 37% of the leaf surface by rust pustules. Vavilov (39A, 40) in 1913 and 1919 published comparable diagrammatic scales for estimating leaf and stripe rusts, with 4 stages designated 1, 2, 3, & 4.

Other investigators have not used diagrammatic scales but have designated rust intensity by descriptive terms ("little", "much", "very much", etc.), or numerals each carrying in the mind of the user the connotation of a certain degree of rustiness. Thus Eriksson and Henning in 1896 (9) recognized 4 degrees of rust intensity, indicated by the numerals 1 to 4 and described respectively as "trace", "sparse", "moderately abundant", and "abundant"; Butler & Hayman in 1906 (4) and Yachevski in 1909 (42) used similar systems; Litvinov in 1912 (17) modified this by adding the intermediate grades 0-1, 1-2, and 3-4, but still identified them only by descriptive terms. Gassner in 1915 (11) agreeing with Nilsson-Ehle (23) who used a similar but 6-grade scale, that 4 degrees of rustiness did not give sufficient diversity, recommended a scale of 8 steps (1=minimum----3=weak----6=strong----8=exceptionally strong) and used these in combination with Roman numerals I-X representing successive stages in the development of the host plant. In Gassner's notation for example, "5 VIII" would indicate medium infection when the host plant was in the post-blossoming stage.

The method of designating degrees of rustiness by numerals and descriptive terms has been assailed by Russian phytopathologists, particularly Naumov (21) and Rusakov (27). They object to the too limited number of the grades of infection in the scales of Eriksson and Henning and Yachevski, and to the use of descriptive terms in all systems in which a standard diagrammatic scale is not used, since such terms as "weak" or "abundant" have entirely different connotations to workers in regions that differ in the amounts of rust normally present. Thus the reports of different workers are not comparable nor can one determine with approximate accuracy the amount of rust corresponding to such terms.

Likewise the diagrammatic modification of Cobb's scale that is in standard use in America has not found favor with the Russian workers. Naumov (21) considers that it is "rough", "schematic", too susceptible to errors of chance, and in ill agreement with the actual distribution of rust pustules on cereal leaves in nature; Rusakov (27) agrees with Naumov.

Another problem in estimating the intensity of rusts lies in the fact that they do not infect all attacked parts of the plant uniformly. It is the rule to find plants in which some leaves have high rust percentages, others have moderate amounts of rust, and still others have none. Without a prescribed practice to follow in appraising rust under these conditions, different workers can come to very divergent conclusions respecting the same intensity of rust. Litvinov (17) met this problem by proceeding on the assumption that the degree of infection is greater in lower than in upper leaves, each leaf being more strongly infected than those above it and more weakly than those below it. (The descriptive terms applied by Litvinov in his scale involve leaf position, e.g. "1-2"=very strong infection of 4th leaf from top; "2"-very strong infection of 3rd leaf from top, etc.). If it were true that rust is progressively less from below upward, knowledge of the position on the plant of any given leaf, together with the degree of its rustiness, would give an approximate picture of the rust intensity for the plant. Litvinov's scale could only be used if rust actually is proportionately less the higher the position of the leaf. Against this assumption Rusakov (27, 43) offers 4 objections: (a) As Litvinov himself recognized, rust does not always proceed from the lower leaves upward, although this is the rule in warmer regions where the moisture conditions about the lower ranks of leaves are more favorable for rust infection. In cases of late-appearing rust in the colder part of Russia (Amur province), Rusakov points out, the uppermost leaves may be most heavily infected, the middle leaves less so, and the lower leaves not at all. (b) Rusakov also emphasizes the importance of including the amount of dead foliage in rust appraisal. This is an indication of the amount of damage done by the rust. In addition, rust may be much more apparent on a plant that still retains a considerable amount of green leaf tissue, as compared with one in which most of the foliage has succumbed, yet the latter may have suffered the more severely from rust. (c) Rusakov also points out that if 2 leaves at different position on 2 plants have an identical degree of rustiness, the plants may be suffering damage of different degrees, since the different leaves on a cereal plant have different functions; the lower ones contribute principally to the vegetative development of the plant, while the upper leaves serve almost exclusively to fill the grain. Hence a given amount of rust on upper and lower leaves respectively may have quite different physiologic effects in the two cases. (d) Finally Rusakov observes (43) that of 2 cereal varieties, variety A may have rust on the first 4 tiers of leaves, counting from the top, to the extent of 4, 4, 4, and 3-1/2 Russian units (see Fig. 1), while variety B has 4, 3-1/2, 3, and 2 units of rust on the corresponding leaves, the former having been infected more strongly and earlier than the latter. If only the top, most heavily infected rank of leaves is appraised, the 2 varieties would be scored as equally strongly affected, but actually variety A has more than twice as many rust pustules per plant.

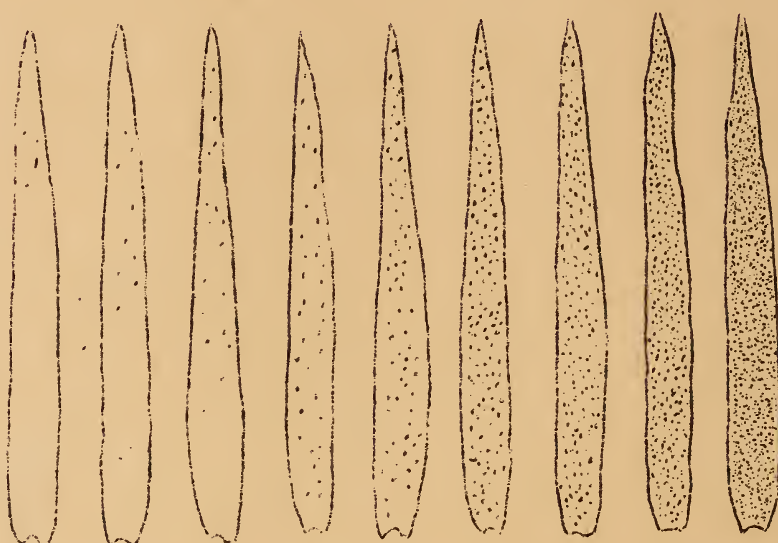
In an endeavor to obviate some of these difficulties and proceed in the direction of greater accuracy in determining degrees of rust intensity, Rusakov (25, 27, 43) developed the following method, which has since been widely accepted and followed by Russian workers:

A diagrammatic scale of 9 degrees of rustiness was prepared as a standard with which to compare rusted leaves. This scale is shown in Fig. 1, together with the numerical symbols 0, 1, 1-1/2, 2, 2-1/2, 3, 3-1/4, 3-1/2, 3-3/4, and 4 "balla" (hereinafter referred to as "Russian units) applied to each grade of rust, and a comparison with the approximate equivalents on the Cobb scale and its American modification. It is seen from the figure that Rusakov's scale includes 3 degrees of rust intensity in the low rust range that have no counterpart in the other scales, in accordance with his observation that 10, 15, and 20 rust pustules per leaf respectively in the first 2 weeks of rust development may lead to major differences in grain yields in the 3 cases.

The Russian scale has degrees of rustiness that progress in logarithmic order; each stage represents approximately double the number of rust pustules per leaf as that of the next lower stage. To reduce the system of

Figure 1. Comparison of Rusakov's rust intensity scale with the Cobb scale and its American modification.

Rusakov Scale:



Russian units:	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{4}$	$3\frac{1}{2}$	3 3/4	4	Designation of intermediate points: $1-1\frac{1}{2}$, etc.
Equivalent to no. pustules:	1-5	6-12	13-25	26-50	51-100	101-175	176-325	326-500	Over 500	
Corresponding values in Cobb scale:	-	-	-	1%	5%	10%	20%	-	50%	20+, 50-, etc.
Corresponding values in USDA modification of Cobb Scale:	-	-	[illegible]	5%	10%	25%	40%	65%	100%	15%, 85% etc.
Russian equivalent units (See text):	.01	.03	.07	.15	.30	.55	1.0	1.65	2.6	

Russian units of estimation to values that may be used in arriving at a single figure representing the degree of rustiness of a whole plant, Rusakov (43) furnishes the "equivalent units" given in the bottom row of Figure 1. These represent the actual number of rust pustules, one equivalent unit corresponding to 250 pustules per leaf. In appraising a variety for rust, the various ranks of leaves (usually 4) are scored in Russian units, these are converted to equivalent units, and the latter are summated to give a figure for the total rust present on the entire plant. Thus in the example given above, of the 2 varieties A and B, A would have had 2.6 + 2.6 + 2.6 + 1.0 = 8.8 equivalent units, while B would have had only 2.6 + 1.0 + 0.3 + 0.07 = 3.97 equivalent units or a total of less than half as much rust as variety A.

This scale is applied to the leaf rusts with the exception of stripe rust (Puccinia glumarum (Schmidt) Erikss. & Henn.) in which case Rusakov follows Naumov's procedure (21) of estimating the percentage of the leaf area involved by rust, unless the number of pustules is less than 20, in which case the number of pustules is stated (Table 1).

Table 1. Russkov's scale for estimating intensity of stripe rust

Rust stage	% leaf occupied by rust	:	Rust stage	% leaf occupied by rust	:	Rust stage	% leaf occupied by rust
1	1-4[a]	:	5	30	:	9	70
2	5[b]	:	6	40	:	10	80
3	10	:	7	50	:	11	90
4	20	:	8	60	:	12	100

[a] Corresponds to 20-90 pustules; [b] corresponds to 100-250 pustules; if number of pustules < 20, the number is stated.

2. Procedure of appraising rust intensity. In general the Russian workers have made a practice of appraising each examined cereal field several times in the course of a growing season. Rusakov (27) recommends 6-7 examinations during the vegetative period, at about 10-day intervals, and emphasizes the particular importance of examinations just prior to heading, at the beginning of blossoming, and in the milk and waxy stages; Brizgalova (3) followed a similar practice.

Furthermore, Rusakov, Naumov, and others feel that it is necessary to treat the different ranks of leaves individually in the examinations. The recommendations on methods of sampling cereal fields given by these 2 workers, which are representative of Russian practices, are as follows:

Naumov in 1924 divided plant diseases into 2 categories: (a) those in which we are interested in the degree of infection and where there is not a simple correlation between the degree of infection and the amount of damage caused by it (e.g. cases of cereal rusts, leaf spot diseases, most downy and powdery mildews, most scab diseases, etc.); and (b) those in which the essential feature is the quantity of infestation, where there may be a direct and simple correlation between the quantity of infestation and that of the loss it produces (e.g. smuts, damping-off, ergot, plum pockets, etc.). The methods of sampling and calculating data differ somewhat in the 2 cases.

Naumov's procedure requires the taking of data of the following types: degree of infection (d); total number of suscept organs per plant (m); number of suscept organs infected per plant (x); total number of plants per field or plot (N); number of infected plants per field or plot (N'); total number of fields or plots per region, experiment, etc. (Q); and number of infested fields or plots per region, experiment, etc. (Q'). Of these quantities, d applies only to diseases in the first category and in the case of cereal rusts is determined by use of one of the scales described in the preceding section; in the case of diseases of the second category, d is total or unity (i.e. except in rare cases a smutted head or ergoty floret is totally worthless). In work with large populations of uniform plants, e.g. cereal fields, N for practical purposes $=\infty$ and thus N and N' are expressed not in absolute terms but as percentages, N equalling 100%.

With cereal rusts, Naumov's procedure involves determination of degrees of infection for top leaves and middle leaves independently, and if necessary, other additional ranks of leaves; he does not specify the number of leaves or plants to be examined per assay, but presumably this would be determined by the degree of variability encountered. Having obtained an average for the degree of infection of all ranks of leaves examined (d) and counted the number of leaves per plant infected or not infected respectively, the work per field or plot is often completed, since with cereal rusts in advanced stages there is 100% infestation and N' = N. Naumov's method of calculating these data to get an over-all estimate of degree of infestation is given in the following section.

Rusakov's method (27) is somewhat less simple than Naumov's, since Rusakov includes data for each rank of leaves and for degree of leaf death as well as of rust infection. The procedure is as follows:

On the approach of the principal phase of plant development, 20 culms of average development are collected at points diagonal to and not less than 2 meters from one another, in places typical for height and density of the plant stand. For each rank of leaves is determined the average height of its attachment; degree of leaf death (in tenths of the leaf surface); and degree of rustiness in Russian units according to Rusakov's scale (Fig. 1). Stem rust is separately but similarly scored according to the respective nodes in which it is found. With such data taken at heading, milk, and waxy stages of plant growth, one has a measure of the dynamics of rust development in relation to time.

To American workers, accustomed to appraising the degree of rust intensity on hundreds of cereal varieties within a few hours, such procedures as those outlined above may seem far too laborious for ordinary practice. This is not necessarily true. With Rusakov's method, the more complex of the two, a worker can appraise 40 varieties in 8 working hours. In many cases, particularly in dealing with important genetic material or in technical studies on rust, the completeness, dependability, and comparability of such objective and accurate methods as those of Rusakov may well outweigh the limitation involved in the requirement of 12 minutes per appraisal.

When the rust is present in extremely small amounts, it is customary for the Russian workers to indicate its amount in terms of the number of minutes or hours of search necessary to find a given small number of infected leaves (23, 26, 27, 29). One must admire the patience shown in such searches; Rusakov, for example, mentions many hours per day of fruitless search during 4 weeks (26), and in another case speaks of eventual success in finding 28 infected plants in a search of more than 3 hours (30). While the personal factor is an important variable in this method, it yields valuable data on the extremely important early spring cycles of infection. A better procedure in such cases would be to record the number of rusted plants found, in terms of the total number of plants examined, as Brizgalova had done (e.g. record of 23 infected plants found in 2000 examined). When rust was more abundant, the latter worker applied Rusakov's scale first to 1000, than 100, 50, and finally 25 diagonally-located plants at different places in the field (3).

3. Calculation of data. While Rusakov gives no special directions for reducing data taken by his methods to over-all averages, Naumov (21) clearly describes his method of accomplishing this by means of the diagram which is reproduced with slight revision in Figure 2.

Ducomet and Foëx (6) have published in French a review of Naumov's survey methods, but their account of his methods of calculation is so inaccurate that it will confuse rather than aid the reader. In turn, Ducomet and Foëx have offered their own suggestions on a method for appraising rust in cereals. In brief, their scale embraces 7 stages of rust designated by numerals, described by terms from "trace" to "enormous", and representing coverage of the leaf by rust pustules of from less than 1/20 to 3/4-total. Each organ of the plant is scored separately, head (glumes and awns, rachis, grain), each internode, numbered 1, 2, 3, etc. from above downward, each leaf and each leaf sheath similarly numbered, and each leaf is divided into proximal, medial, and distal sections and each of these is separately scored as to the degree of its rustiness. Each part that is scored is assigned a coefficient to weight the readings according to the importance attached to each, and the rust intensity is calculated by the use of previously prepared tables. At any given examination the authors recommend 6 scorings for heads and 3 each for leaves and stems, and they suggest that examinations be made at boot, heading, and post-blossoming stages of the host plant and 3-4 times thereafter.

The method of Ducomet and Foëx has as its goal the reduction of rust infection of the entire plant to a single absolute value. It is felt by the writer, however, that while granting the desirability of such an objective, and provisionally assuming that the procedure is theoretically sound, the amount of labor involved so reduces the number of examinations that are possible, that more accuracy may be lost through restriction of the number of specimens examined than is gained by the greater detail of each examination.

In passing, brief reference should be made to the method of evaluating cereal rust intensity that is in general use in the United States. Data are taken, with the aid of the U. S. Department of Agriculture modification of the Cobb diagrammatic rust scale, on severity (average degree of rustiness of leaves or stems), prevalence (percentage of plants affected in any degree), and response (type of lesion produced). The over-all expression of rust intensity is the coefficient, which is the product of severity x response.

1. Degree of disease per organ = d
2. No. infected organs per plant = x

→ Average infection of organs = $\frac{d_1 + d_2 + \text{-------} d_x}{x}$ = F

3. Total no. organs per plant = m

→ Average infection of plant = $\frac{F.x}{m}$ = P

4. No. infected plants per field = N'
5. Total no. plants per field = N

→ Average infestation of field = $\frac{P.N'}{N}$ = A

6. No. infested fields in region = Q'
7. Total no. fields in region = Q

→ Average infestation of region = $\frac{AQ'}{Q}$

<u>Special cases</u>: When all plants are infected, N' = N and A = Fx/m. When all organs on the plant are infected, x = m and P = F; if at the same time all plants in the field are infected (a common case with cereal rusts), A = F. i.e. the average infestation of the field = the average infection of the organs of the average plant. For diseases in which d is unity or total (e.g. smuts), d can be omitted and P = x/m. For ergot, d, the degree of infection of the different spikelets, is constant, and can be omitted; here, however, an additional step in the observations is required, i.e. determination of the total number of spikelets per head and of the average number of these which are infected. If the fields of a region are not uniformly infected the last calculation would have the form $(A_1 + A_2 + \text{----} A_{Q'})/Q$ and it would be necessary to weight each "A" value according to the number of acres in the field.

<u>Figure 2. Naumov's (21) method for calculating disease intensities.</u> (Slightly revised. Means of gathering data are given in preceding section).

A comparable method has been proposed by Tehon (39). Diseased plants that are found are grouped according to their distribution in one or another of the grades (0, 5, 10, 25, 40, 65, and 100%) of the modified Cobb scale. The frequency of plants in each grade is multiplied by the percentage of that grade, these products are summated, the sum is divided by the total number of plants in all grades, the result, expressed as a percentage, is multiplied by the percentage of diseased culms in the field, and the final product is taken as a measure of estimated rust for the field.

III. METHODS OF DETERMINING DESTRUCTIVENESS OF RUSTS

Naumov has published a detailed review (22) of the various means used in Russia for determining the losses caused by cereal rusts. In the following account his classification is followed with some additions.

1. Greenhouse methods. Under the controlled conditions of the greenhouse it is not difficult to produce different degrees of rust infection on otherwise similar plants, to measure their respective yields, and thus to arrive at a conception of the damage caused by rust of definite intensity acting over a definite period in the life of the plant. No one can deny the possible error in equating such losses with those suffered by plants growing under natural conditions in the field, due to the artificial conditions of the greenhouse and ~~the resulting~~ abnormalities in host-plant development; however, such greenhouse tests undoubtedly cast some light on the destructiveness of rusts, particularly when their results are combined with those from other methods of study.

In addition to American work with this method, as exemplified in the studies of Mains (19) and Johnston (15), Naumov (22) reports that Rusakov and Shitikova in 1932 found in greenhouse experiments that if wheat was infected with leaf rust 2 weeks before heading, the rust becoming medium-strong before blossoming and remaining strong thereafter, yields were reduced by 70%; with similar infections that did not become strong until the milk stage the yield reduction was 59-62%. Rusakov (32) observed an 18% reduction in yield when greenhouse wheat plants were inoculated with leaf rust 4 or 6 days before the milk stage.

2. Method of artificially removing foliage. Since leaf rusts reduce the photosynthetic area of cereal plants, it might be thought that some clue as to the destructiveness of the rusts might be gained by artificially removing leaf tissue at different stages in the development of the host plant, and determining the influence of this on yield. Such experiments have been carried out by workers in various countries (Roebuck and Brown in England, Rudorf, Job, and Rosenstiel in Argentina, Kiesselbach in Nebraska, etc).

Russian workers have also used this method of investigating rust losses (Rusakov 31, 32, 43; Eidelman, 7, 8; Shevchenko, 36; and Lubimenko, mentioned in Naumov (22) without recognizable citation). Rusakov, for example, found that removal of one leaf 15 days before its normal death reduced grain yield by 10%. He also removed all leaves from plants that had the equivalent of 2-1/2 green leaves; a week later the non-mutilated check plants had only 1-1/2 green leaves and 5 days later all had died normally. Despite this small difference in possible photosynthesis between mutilated and check plants, the latter produced 8.5% more grain than the former.

Eidelman (8) summarizes experiments with Telichko, Siriachenko, and Shevchenko in which 25 to 50% of wheat leaves were removed at different stages of plant development. Yields were reduced in proportion to the amount of foliage removed. In Belaya Tserkov yields were reduced 54.9% by removing all leaves at heading stage, while if only the lower leaves were removed in the blossoming to milk stage the reduction was 17-20%. At Kiev the yield reductions were less, which was attributed to growing conditions at Kiev that favored the greater photosynthetic activity of the remaining foliage.

It has been well pointed out by Shevchenko (36) that the results on yields of removing leaves are not entirely comparable to the destruction of those leaves by rust. In all probability the losses from leaf rust are greater than the leaf-clipping experiments would indicate, since rust, in addition to reducing photosynthetic surface also results in excessive transpiration such as does not occur in leaf-clipping experiments, and also, in the latter, the uncut leaves remain green longer than they would otherwise, and thus compensate to some extent for the loss of leaf tissue.

3. Method of comparing yields in years of different rust severity. If average cereal yields for a series of rust-free years are compared with yields during years of rust severity, other factors being as comparable as possible, the differences in yields in favor of rust-free years may serve as an index of the amount of loss caused by rust. This method of arriving at the extent of crop loss due to rusts has commonly been followed in early work with rusts and even up to the present, particularly in the United States.

The inadequacies of such a method are obvious. Severe rust losses occur in years of ample rainfall; and in regions in which low rainfall is a limiting factor in cereal production, the losses caused by rust in "wet years" may to a great extent be offset by the increased level of production due to adequate moisture for growth of the host plant. Hence in such areas the differences in yields between years of severe rust and rust-free years may indicate only a small part of the reduction in potential yields during years of rust severity.

Another grave fault in this method lies in the inability to give equal value to estimates of rust severity in different years. It has been well established in the United States, for example, that wheat leaf rust and the losses caused by it were grossly underestimated prior to 1930.

Naumov (22) cannot agree with Ružinov (cited in 22; probably 34) that this method only leads to "absurd conclusions". Two comments seem applicable: (1) the value of loss estimates based on comparative annual yields increases with the number of positive cases in which lowered yields are associated with years of severe rust, and with the lack of conflicting cases it is a problem in the statistical treatment of heterogeneous data; and (2) again it may be emphasized that no method gives completely unchallenged results in determining rust losses, but the resultant conclusion from several methods is highly significant; this method by itself may have but very limited value, yet it may be of considerable importance in serving to confirm and add to the testimony of other methods for determining loss due to rust.

4. The historical method. By this Naumov refers to a comparison of yields before and after some fundamental change has occurred in the culture or environment of the crop, such as to markedly affect its pathology; e.g., the widespread adoption of an effective control measure, or the general and destructive invasion of a crop by a formerly unknown or unimportant disease. Naumov's choice of barberry eradication in North America as an example was an unfortunate one; it did appear in the early 1930's that this had led to a fundamental increase in wheat yields through reduction of stem rust, but the epiphytotics of 1935, 1937, and 1938 fully disprove this thesis. A better example would be the case of sugar cane in relation to mosaic. The establishment of this disease was associated in Louisiana with a fall of sugar production from 400,000 tons to about 50,000 tons per year, and the subsequent adoption of mosaic resistant varieties raised production nearly back to its former level. Here the historical method affords striking and unequivocal evidence of the amount of crop loss caused by a plant disease.

5. Method of comparing yields of susceptible and resistant varieties. If 2 assortments of cereal varieties, one susceptible to rust, the other resistant, are found as groups to produce approximately equal yields under rust-free conditions, while yield advantage in the resistant group is seen when the 2 groups are exposed to rust, the yield difference may be taken as a measure of the loss sustained in the susceptible varieties as a result of the rust attack. The reliability of this method increases with the numbers of varieties in the groups, the equality of their yields in the absence of rust, and the correlation between rust intensity and yield difference.

Instead of grouping the varieties they may be arranged in a progressive series from the variety of highest yield to that of lowest yield under rust attack. If then the disease intensity is found to be inversely correlated with the yield for each variety, the relationship between rust increase and yield decrease is a measure of the loss caused by the rust, its reliability being determined by the height of the correlation.

Data of this sort may be treated by any of several methods. One of these is exemplified in Salmon and Laude's experiments with 24 varieties of winter wheats in Kansas in 1929 (35). When the varieties were arranged according to descending yield, disease intensities of the same varieties plotted on the same coordinates lay on a fairly regular ascending curve; i.e. the greater the rust in any given variety the less its yield, with high regularity.

Starkov (38) reports tests with 6 strains of wheat varying from highly resistant to highly susceptible toward leaf rust at 5 Russian experiment stations in 1933, 1934, and 1935. A striking advantage in yield is correlated with degree of rust resistance. For example, at Krasnodar in 1935 the resistant strains Kanred x Fulcaster, Illini Chief, and Hybrid 622 showed rust intensities of .05%, .12%, and .00% and yields of 31.7, 31.8, and 29.0 tsenters/hectare respectively, while in the same test the susceptible strains Stavropolka 0328 and Ukrainka showed 68.5 and 65.0% of rust and yielded 17.0 and 10.5 ts./ha. respectively.

At the Omsk Experiment Station, Rusakov and Pokrovski (33) have noted that under rust-free conditions the susceptible soft wheats usually outyielded more resistant hard wheats by as much as 20%. Under the conditions of severe leaf rust in 1928, however, the latter outyielded the former by 41%, collectively and individually. Throughout the 1928 tests, yields and leaf rust intensity were inversely correlated between and within groups of varieties.

6. Method of comparing yields with degree of infection in selections from varieties or groups of lines from segregating hybrid familes. This method is a further refinement of the last, inasmuch as the resistant and susceptible plants are more comparable genetically. In the first case, it assumes that a disease-resistant selection from a disease-susceptible variety will differ little from the parent variety except in disease reaction and that a comparison of yields with disease intensity in the two cases will give a true picture of the effect of a given intensity of disease on yield. In the second case it assumes that a group of disease-resistant lines from a resistant x susceptible cross will differ from a group of susceptible lines from the same cross on the average principally in disease resistance alone; the larger the numbers of such lines used, the greater the probability that this will be true and that there will be a high correlation between disease differences and yield differences. An objection to the method is the theoretical possibility that the selection may differ from the parent variety in other characters of yield importance in addition to disease reactions, or of genetic correlations of such a nature that rust reaction and some other factor of yield importance do not segregate independently; there is no good evidence, however, that these have been faults in the majority of this type of experiments.

This method, which has often been used in the United States (e.g. in the work of Waldron (41) and Johnston (16)), has also been turned to good account with reference to wheat leaf rust by Shevchenko and by Rusakov's students Lukyanenko and Pronichev, and to stem rust by Rusakov and Panchenko (cited in 22). Lukayanenko (18), for example, grouped 187 wheat lines from crosses between susceptible and resistant parents into 3 classes, showing 0-5% rust, 25-40% rust, and 65-100% rust respectively. The least infected group exceeded the most heavily infected group in grain yield (av. 26.7%), yield of straw and chaff (25%), proportion of grain to bulk of the plant (11%), and 1000-kernel weight (17.1%), all with high statistical significance. The group of intermediate rust susceptibility was also intermediate in all of these yield factors.

7. Individual method. Ruzinov (34) believes that the only way of getting reliable results correlating rust severity with yields under field conditions is to select and compare individual plants from the same field, that differ in rust attack. Finding a correlation between shortness of culms and severity of rust, he recommends random collecting of severely, moderately, and slightly infected plants in a given field, grouping of the

plants in each infection class in 5-6 subclasses according to length of culm (exclusive of the uppermost node), and determining the yield in each class in relation to that of the subclass with the longest culms. His work was principally with stripe rust, to a less extent with stem rust and crown rusts. Naumov (22) feels that the method is highly accurate and may have promise, but needs much further testing, especially for leaf rusts.

A criticism that might be levelled regarding the individual method is this: if there is considerable variation in degree of rust attack among different plants in a field (and there must be for the method to be applicable) this variation must be the result of microclimatic differences (24) in the field, and these differences would have varying effects on the yields of individual plants quite apart from the influence of degree of rust intensity. In other words, the differences in yield obtained have been produced by a number of factors of which rust is only one, and it appears to the writer that errors from yield differences due to other factors than rust are likely to be much greater with the use of this method than with some of the other means of determining rust losses.

8. Comparison of yields from plots protected with fungicides with yields from unprotected plots. This method has been used more extensively than any other in determining cereal crop losses due to rusts and other diseases. American workers are familiar with the extensive work along this line that has been done in the United States (Galloway, 1894; Stakman, 1927; Mains, Caldwell, 1927-1934; Johnson, 1931; Decker, 1935; Butler, 1937-1940, etc.), in Canada (Greaney and Bailey, 1928-1941; Peturson and Newton, 1939), and in Australia (Neill, 1931; Phipps, 1938), and no attempt will be made to review this work.

In Russia work of this type has been done by Rusakov (in 22, 43), Pronicheva (in 22) and Brizgalova (3). Brizgalova's experiments are subject to the same criticism that applies to those of practically all other workers who have attempted to protect cereals from rust with fungicides, namely that dusting with sulphur was begun after the rust had already made enough headway to have become noticeable in the field. Her results in 3 years of extensive experiments with wheat leaf rust in Siberia show notable rust losses that could be reduced by protecting the plants with a fungicide, yet in all cases her comparisons are between different degrees of rustiness and not between rusted and non-rusted plants. To reduce her data to absolute terms she used a method of calculation which starts with an assumption of Rusakov's that 10% leaf rust has no significant effect on yield. The calculations proceed as in the following example. In 1933 control plants had 60% rust while dusted plants had 30%, and there was a 22.1% difference in yield in favor of the dusted plants. In 1934, when control plants had 30% rust and dusted ones 10% (considered as producing no loss), the latter outyielded the former by 9.7%. Therefore the absolute loss from rust in 1933 was considered to be 22.1% + 9.7% = 31.8%. In this way Brizgalova obtained values of yield reductions from rust varying from 9.7% (maximum of 30% rust in the waxy stage) to 70.2% (maximum of 100% rust in the blossoming stage).

Naumov (22) has justifiably criticized Brizgalova's method of treating her data. She assumes that each equal increment in percentage of rust above 10% has an equal effect in reducing yields, which is questionable, and even if this were the case, the calculations should include reducing to terms of 100% and multiplying rather than adding.

The Russian workers, as Greaney and others, have found that the amounts of sulphur used in dusting have no fertilizing or other effect on the soil such as would influence yields independent of rust control (Shitikova-Rusakova and Rusakov, cited in 22).

9. Topographical method. As employed in Russia, this involves the selection in different parts of a field of groups of plants, each group differing from the others in the degree of its disease intensity, but in general being comparable to the other groups in other regards (variety, time of sowing, cultural practices, etc.). Protection from or exposure to environmental factors and exposure to air-borne inoculum are common reasons for such differences in disease intensity. The method has been used by Rusakov (25) and Grushevoi (cited in 22) with stem and crown rusts. Rusakov found yields ranging from 88.6 to 28.1 units in plant groups with from .3 to 3.6 Russian units of rust respectively. Grushevoi determined yields of 100, 81, and 55% in differently located plots showing little, moderate, and severe crown rust respectively. Naumov feels that this technique is very promising but needs more methodological study.

10. Comparison of anticipated with actual yields. Yields of cereals, when the harvest is in, are often but shadows of the bountiful crops anticipated by growers and crop scouts a month or two before harvest. Hail, drought, hot winds, floods, insect enemies, and diseases, any or several of these may have had their part in disappointing expectations.

As illustrated in the following example, a comparison of expected with actual yields, making due allowance for the various factors that have depressed the yields, is a means, albeit a very subjective one, of estimating the relationship between disease and crop loss. In 1921, a severe wheat leaf rust year in Indiana, Gregory (13) compared the wheat harvest anticipated in May with the actual yield in August, and dividing the difference among the different factors producing reduction in yield, placed the loss due to leaf rust in the neighborhood of 10%. Since time immemorial this has been the method of farmers in accounting for crop losses. Without an adequate background of understanding of the nature and relative importance of loss factors it may be inaccurate and misleading in the highest degree; the most recent, unusual, or most obvious deleterious factor is usually accused of all or nearly all of the destruction, and less obvious or less well-known factors may not enter into the account at all. The method of comparing theoretical and actual yields takes on some significance, however, when it is properly used with adequate understanding of the factors involved, as seen in the work of Shitikova-Rusakova cited by Naumov (22). She grouped culms according to amount of rust and determined the yields for each group. From these data she could plot a regression line depicting the relationship between percentage of leaf surface rusted (abscissa) and percentage of crop loss (ordinate). Actual losses (in tsentners per hectare or bushels per acre) could then be obtained by solving for x (theoretical 100% yield) in the following proportion, and subtracting the actual yield from x.

Actual yield : x = (100% - % of crop loss (taken from regression line)) : 100%[1].

Fig. 3 gives the regression line in one of Shitikova-Rusakova's tests.

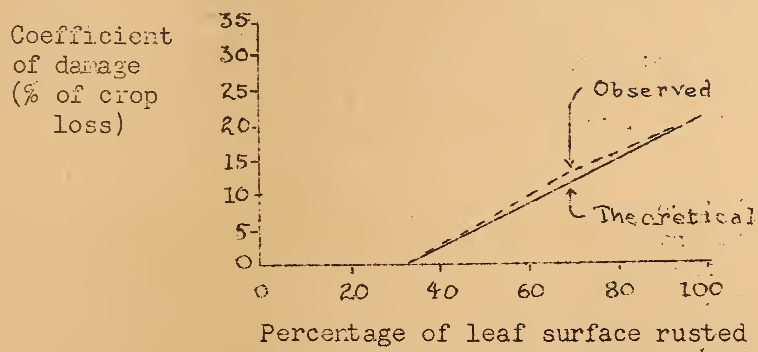


Fig. 3. Rust-loss relationship of wheat variety Ukrainka. Slope of curve indicates that for every 10% increase in rust, the yield is lowered 3.09 per cent. (From Shitikova-Rusakova, in Naumov, 22.)

11. Combinations of the above methods. A combination of the topographical method and that of sulphur dusting in the field was used to good advantage by Gassner and Straib in Germany (12). The principles were those of the topographical method (Subsection 9, preceding) except that Gassner and Straib created diversity among groups of plants in the field by a variety of treatments including protection from rust with sulphur, and variation of the planting date. A similar device has been used with the individual plant method (Subsection 7, preceding) by Shitikova-Rusakova (in 22).

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[1] This is essentially the method followed in calculating crop losses in the U. S. Dept. Agr. Pl. Dis. Reporter (Supp. 12:308. 1920 and Supp. 83: 1-3. 1932) with the exception that Shitikova-Rusakova has prepared her regression line by use of the formula: $M_y = R \frac{y}{x} (x - M_x)$ where M_y = average absolute grain weight observed from uninfected culms, $R \frac{y}{x}$ = the lowering of absolute weight according to height of culms in comparison with uninfected culms, x = average height of culm infected to any given degree, and M_x = height of healthy culms. The reason for including culm length in the calculations is to avoid errors due to differences in rust-yield relationships between main culms and secondary tillers. The measurement is made from the base of the culm to the insertion of the uppermost leaf.

Experiments of Brizgalova in dusting wheat, with a criticism of her method of treating her data, were reported in subsection 8. In addition she derived losses from wheat leaf rust in a "rust year" by comparing yields under conditions of various degrees of infestation with yields from comparable plantings in a "rust-free year." This gave a series of loss percentages that ranged from 1.01% loss with weak (40%) rust at the beginning of the milk stage to 67.5% loss with strong (100%) rust in the blossoming stage. These loss percentages were ranged beside the loss percentages that she obtained through her calculations from dusting experiments. For final estimations of losses she took the numerical mean of the 2 values for rust loss at each level of rust intensity. This procedure has the advantage of giving results that are the average of 2 distinct methods of work; thus errors introduced in either one procedure may be somewhat reduced.

12. <u>The questionnaire method</u>. The use of questionnaires should not be overlooked in an enumeration of the methods of arriving at estimates of crop losses due to diseases. Russian phytopathologists, as those in other lands, have exhibited some mistrust of the results of using questionnaires on plant diseases directed at laymen who usually have no background for evaluating pathological phenomena. Prior to embarking on the Russian program of research on the cereal rusts of the past 25 years, questionnaires were used to determine the status of these diseases in Russian cereal production. In some cases the results were none too good and at the All-Russian Botanical Congress in 1920 it was emphasized that in general only 10-20% of the questionnaires were returned. Rusakov (29), however, had a much better experience in 1924 when he sent 700 copies of a cereal rust questionnaire to correspondents (usually chancellors of the various governmental administrative units) in Siberia (Amur, Primorsk, and Za-Baikal provinces). Of these 54% returned the questionnaires duly filled out and often with additional comments.

With as many replies as this it is possible to attach significance to the summarized replies to some of the questions. With regard to importance of the cereal rusts and the damage caused by them, Rusakov was able to extract the following, apparently well-authenticated information: In eastern Siberia wheat suffers much more from rust than the other cereals; total crop losses from rust occur in all these provinces but especially in Primorsk[2]; between 1917 and 1926 there was a marked reduction in wheat acreage in Primorsk as a result of repeated losses from rust; rust was associated with lodging and early maturity; both leaf and stem rusts were involved; rust usually appeared suddenly, at heading to blossoming stage, or in most cases, soon after the blossoming stage. Other questions regarded environment in relation to rust.

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[2] Comments added were often significant: "Expected 75 pood (50 bu.) but obtained nothing"; "Crop entirely destroyed,--only straw; not gathered"; "No harvest whatsoever"; "Wheat was abandoned for grain".

The amount of detailed information gleaned by Rusakov from this questionnaire, which is little more than suggested in the preceding paragraph, well exemplifies the value of the questionnaire, under favorable circumstances, as a means of eliciting information on crop losses due to plant diseases. It is patent that individually most or all replies must be regarded with caution, and it is also well known that large majorities of layman correspondents can be mistaken on certain matters pertaining to plant diseases. Some of the shortcomings of the questionnaire decrease with increase in the number of correspondents and judgment with which they are selected, and if the information forthcoming is properly summarized and conservatively interpreted, the questionnaire can be a most useful survey tool.

13. Miscellaneous methods. The pathologist should be alert to discover clues of losses from plant disease in residues of the crop that for one reason or another have been preserved for several or many years. Rusakov (31) was able to determine the severity of rust and its presumptive destructiveness in early years, for which no field records were available, by examination of sheaves that had been preserved for exhibition or other purposes. The writer also found an interesting clue to the destructiveness of crown rust of oats many years past in the abundance of telial pustules present on the straw of a beehive that had been constructed as an exhibit to illustrate straw hives used in Russia.

Barclay in India (1) attempted to determine rust damage in early years by comparing the price of wheat in given years with the meteorological conditions known to be conducive to rust. While there were some inconsistencies there was evidence of a correlation between high prices, poor yields, and conditions favoring rust (high humidity in January-March). The limitations in this method are obvious: price is regulated by many factors other than crop catastrophes and many crop catastrophes other than rust; futhermore our knowledge of the environmental conditions necessarily associated with rust is far from adequate to lead us to the conclusion that a certain year must have been a "rust year" because of its weather. Despite these shortcomings, such a procedure as Barclay's is not entirely without value, as it does provide an inkling, even though it be a very conditional one, of epiphytotics of years long gone by.

14. Conclusions on methods of determining destructiveness of rusts. No one method for determining cereal crop losses due to rusts can be recommended to the exclusion of the others. Each has its advantages, its contributions, and its limitations. Certain methods can be used under circumstances where others cannot. Combinations of two or more methods are often much more desirable than one alone. The more methods that can be used to bring evidence to bear on this question, the more reliable will be the conclusions. Errors involved in the use of one method can be annulled or corrected by another.

Certain of these methods have been used to almost no extent in America, yet they have contributed valuable data in the hands of Russian phytopathologists; this applies in particular to the topographical and individual methods, and to some extent to the procedure of comparing anticipated with actual yields. This last requires further methodological studies in regard to calculation of data, but has promise of being one of the most exact of all these techniques.

Comparison of yields, under rust attack, of host strains that are genetically similar but differ in rust susceptibility, if carried out on a scale that permits analysis of statistical significance of results, is a means of ascertaining disease-loss relationships that is deserving of much more attention by American workers. By such means as this, based on carefully conducted field experiments and judicious interpretation of data, we can provide the necessary background for rapid and accurate estimates of crop losses by field men in their plant disease surveying.

Any method of determining losses from crop disease depends first of all on accurate determination of intensity of disease and understanding of the dynamics of its development in relation to developmental stage of the host plant. The methods which we have used in appraising the intensity of cereal rusts are not beyond reproach. There is much merit in the methods used by Russian phytopathologists, particularly those of Rusakov described in Section II, preceding; these warrant our careful study, trial, and in some cases, perhaps, our adoption of them or modifications of them in which their better features are presented.

While this review has been concerned almost exclusively with cereal rusts it will be apparent to the reader that the techniques described have a much broader application in the field of plant disease surveying. To cite but a few examples: workable diagrammatic scales, such as are used for rusts, and such as Tehon (39) has prepared for leaf spot disease of oats and wheat, might well be applied to the more exact determination of intensiveness of leaf spot diseases of many other crops besides cereals; the methods of comparing yields of varieties or strains that are genetically similar but differ in disease resistance should prove useful in determining loss from such diseases as bacterial blight of cotton, in which the disease produces such diverse types of injury as almost to defy attempts at loss estimation by other methods; the topographical and individual methods that have hardly been recognized in America, offer possibilities for accurate disease-loss determinations for a variety of types of plant diseases. Except in a few instances, the lack of system and the crude approximations of many of our survey methods today demand that our minds and experiments be directed at plant disease surveying at the research level if the results of our surveying in years to come are not to be huge masses of indigestible data incapable of analysis and synthesis into basic phytopathological principles.

IV. APPENDIX. EXAMPLES OF WHEAT LOSSES FROM RUST (PRINCIPALLY *Puccinia triticina*) IN RUSSIA.

Year	Geographic area	% loss	Rust species	Authority	Reference
General	Russia except North Caucasus	10-20	P. triticina	Grooshevoi & Maklakova	14
1927-32	Russia (average)	10	P. triticina	Shitikova-Rusakova	37
1921	Asiatic Russia	71	P. triticina	Estifeev	10
1926	Asiatic Russia	>75	P. triticina, P. graminis	Rusakov	28
1927, 1932	Asiatic Russia	30-35	P. triticina	Brizgalova	3
1928	Omsk	41	P. triticina	Rusakov & Pokrovski	33
General	North Caucasus; Southern Ukraine	50 often	P. triticina	Grooshevoi & Maklakova	14
1932-37	North Caucasus	50	P. triticina, P. graminis, P. glumarum	Beilin	2
1933	Krasnodar	27.7	P. triticina	Lukyanenko	18
1935	Verblud	50	P. triticina	Pronicheva	In 22

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